Materials Science and Engineering C 62 (2016) 439–443

Contents lists available at ScienceDirect

Materials Science and Engineering C

journal homepage: www.elsevier.com/locate/msec

Is cell viability always directly related to corrosion resistance of stainless steels?

E. Salahinejad [a,*], M. Ghaffari [b], D. Vashaee [c], L. Tayebi [d,e]

[a] Faculty of Materials Science and Engineering, K.N. Toosi University of Technology, Tehran, Iran
[b] Bruker AXS Inc., 5465 East Cheryl Parkway, Madison, WI 53711, USA
[c] Electrical and Computer Engineering Department, North Carolina State University, Raleigh, NC 27606, USA
[d] Department of Developmental Sciences, Marquette University School of Dentistry, Milwaukee, WI 53201, USA
[e] Department of Engineering Science, University of Oxford, Oxford OX1 3PJ, UK

ARTICLE INFO

Article history:
Received 25 September 2015
Received in revised form 22 December 2015
Accepted 29 January 2016
Available online 1 February 2016

Keywords:
Nanostructures
Medical-grade stainless steels
Corrosion
Stem cell viability

ABSTRACT

It has been frequently reported that cell viability on stainless steels is improved by increasing their corrosion resistance. The question that arises is whether human cell viability is always directly related to corrosion resistance in these biostable alloys. In this work, the microstructure and in vitro corrosion behavior of a new class of medical-grade stainless steels were correlated with adult human mesenchymal stem cell viability. The samples were produced by a powder metallurgy route, consisting of mechanical alloying and liquid-phase sintering with a sintering aid of a eutectic Mn–Si alloy at 1050 °C for 30 and 60 min, leading to nanostructures. In accordance with transmission electron microscopic studies, the additive particles for the sintering time of 30 min were not completely melted. Electrochemical impedance spectroscopic experiments suggested the higher corrosion resistance for the sample sintered for 60 min; however, a better cell viability on the surface of the less corrosion-resistant sample was unexpectedly found. This behavior is explained by considering the higher ion release rate of the Mn–Si additive material, as preferred sites to corrosion attack based on scanning electron microscopic observations, which is advantageous to the cells in vitro. In conclusion, cell viability is not always directly related to corrosion resistance in stainless steels. Typically, the introduction of biodegradable and biocompatible phases to biostable alloys, which are conventionally anticipated to be corrosion-resistant, can be advantageous to human cell responses similar to biodegradable metals.

1. Introduction

One of the main requirements for any biomaterial is biocompatibility, the term which refers to a collection of interactions between the material and body tissues. Analyzing cell attachment and viability on surfaces is currently regarded as an essential indicator of biocompatibility [1–3]. This cell/substrate interaction is affected by different features of the biomaterial's surface, including roughness, wettability, released species type, and ion release rate [4–9]. Among them, it is known that the ion release rate can be directly related to corrosion rate, especially uniform corrosion instead of localized types [10,11]. Thus, electrochemical corrosion measurements like impedance spectroscopy (EIS) and potentiodynamic polarization, measuring uniform corrosion rate, can be used to qualitatively estimate and compare cell viability [10–12].

With regard to biodegradable metallic biomaterials like magnesium-based alloys, corrosion products fundamentally are advantageous to biological processes, since released ions are essential species for the body and help healing mechanisms [13–15]. However, for the conventionally used metallic biomaterials designed to be biostable, including stainless steels (AISI 316L), corrosion is deleterious to the body. This is due to the fact that these alloys are composed of some elements that are harmful to the body, especially at high ion release rates [16]. For example, nickel is known to cause allergic reactions on the skin. To resolve this issue, nickel-free stainless steels are being developed [16–20]. Note that the corrosion produces of other constitutes can be still disadvantageous when releasing at high levels, for example chromium.

In ASTM standards, two nickel-free medical-grade stainless steels have been introduced: ASTM ID: F2229 and ASTM ID: F2581. Recently, the structure and some properties of powder metallurgy (mechanical alloying and liquid-phase sintering) samples with the latter standard composition were investigated [21–23]. Typically, it was found that a higher resistance to uniform corrosion, estimated from EIS experiments, dictates a more cell viability on the surfaces, albeit when liquid-phase sintering was completely activated [10]. Nevertheless, the question is whether this conclusion is universal, i.e. whether corrosion resistance is always directly related to human cell viability for this type of alloys.

* Corresponding author.
E-mail addresses: salahinejad@kntu.ac.ir, erfan.salahinejad@gmail.com (E. Salahinejad).

http://dx.doi.org/10.1016/j.msec.2016.01.091
0928-4931/

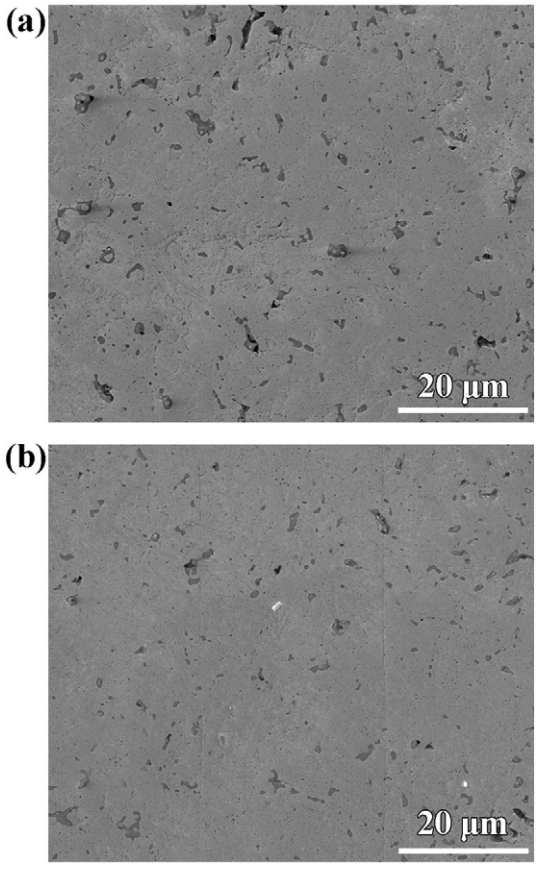

Fig. 1. SEM micrograph of the samples sintered at 1050 °C for 30 (a) and 60 (b) min.

This study focuses on this null hypothesis, where this correlation for complete and incomplete liquid-phase sintering of a medical-grade nickel-free stainless steel was checked.

2. Experimental procedure

Nickel-free stainless steel powders with the chemical composition of ASTM ID: F2581 (Fe–17Cr–10Mn–3Mo–0.4Si–0.5N–0.2C) were first prepared by mechanical alloying, then mixed with 3 wt.% of pre-alloyed Mn–11.5Si powders as a liquid-phase sintering agent, and finally sintered at 1050 °C for 30 and 60 min. The elemental chemicals were supplied by Merck, Munchen, Germany. This sintering temperature was selected since the melting point of the eutectic additive is 1040 °C [21]. A scanning electron microscope (SEM, Hitachi S-4800) and transmission electron microscope (TEM, FEI-Tecnai G2F30) equipped with energy dispersive X-ray spectroscopy (EDX) were used to characterize the resultant microstructure after sintering.

Electrochemical impedance spectroscopic (EIS) experiments were performed on the samples in the simulated body fluid (SBF) [24] at 37 °C under the naturally aerated condition, after 48 h of immersion in the SBF to get a steady-state condition, over ten frequency decades from 5 kHz to 10 mHz with an excitation potential amplitude of 10 mV at the open circuit potential. Also, the sample surfaces after 15 days of immersion in the SBF were studies by SEM. Three replicates were performed for the corrosion tests.

For the assessment of cell viability, the polished stainless steel samples were sterilized by autoclaving at 134 °C for 20 min. Afterwards, a concentrated (500,000 cells/mL) adult human mesenchymal stem cell (hMSC) suspension was seeded onto the tissue culture plastic (TCP) surface (as the standard) and each sample. After one day, the sample

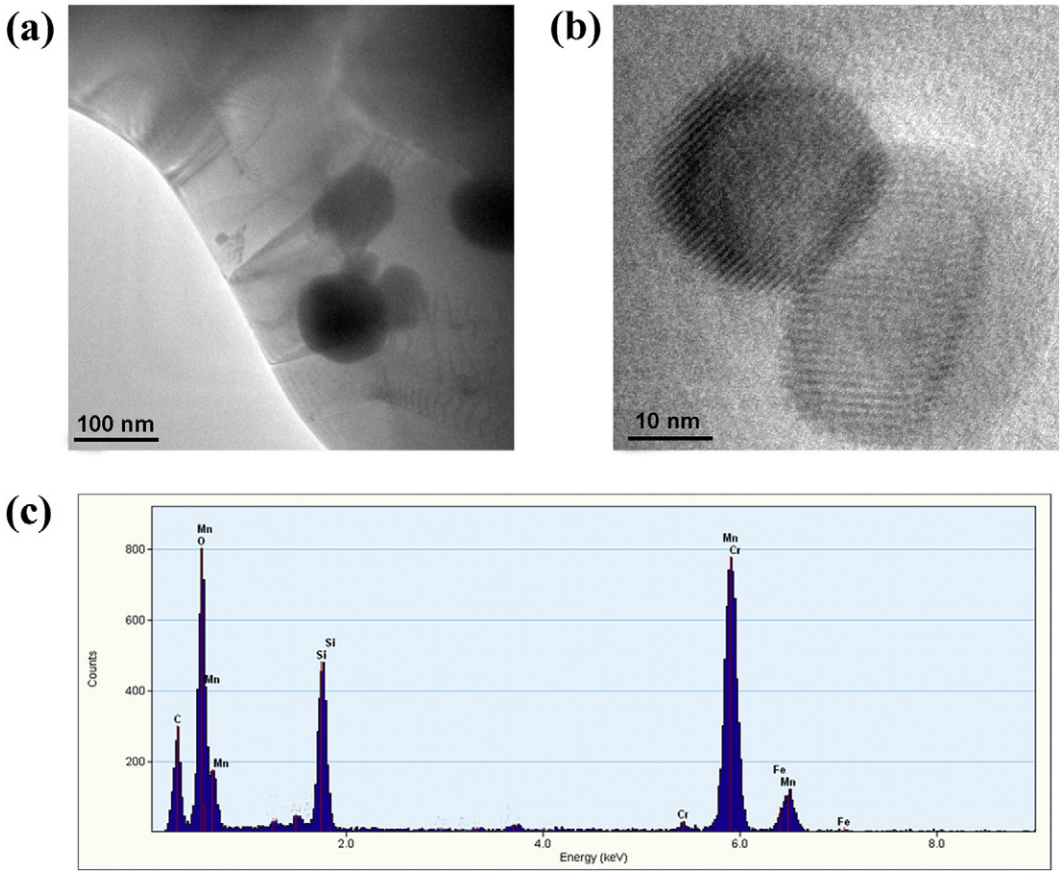

Fig. 2. TEM micrograph (a) of the sample sintered for 30 min, high-magnification TEM micrograph (b) and EDS spectrum (c) of a nanometric dark island in (a).